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F. W.

Operations Research Applications in Forest Fire Management Systems

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OPERATIONS RESEARCH APPLICATIONS IN FOREST FIRE MANAGEMENT SYSTEMS

by

Frederick W. Bratten and James B. Davis

Forest Fire Laboratory
4955 Canyon Crest Drive
P.O. Box 5007
Riverside, California 92507

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Forest fire suppression forces may build up, within a few days, to levels of hundreds or thousands of men, machines and aircraft on a major fire. The problems of efficiently mobilizing, directing, and maintaining such forces, often under difficult environmental conditions, are challenging indeed. Operations research techniques are finding increasing use in attacking some of these problems. The U.S. Forest Service Forest Fire Laboratory at Riverside, California has a small O.R. group working in this area. At present, work is concentrated on exploration of the use of on-site or remotely linked ADP equipment to aid in solving some of the on-line fire management problems. A data storage and retrieval system for fire environment (INFORMAP) is in a preliminary development stage. Other computerized aids being studied are an optimizing initial attack force dispatching model, a fire suppression resource allocation model, and a stochastic fire spread simulation model.

More than 1.1 billion acres of forest lands in the United States require protection from fire. Each year, from 100,000 to 175,000 fires flare up on these lands. In 1966, a total of 4.6 million acres was consumed by fire. In more graphic terms this acreage is a strip of burned area $2\frac{1}{2}$ miles wide stretching from New York to San Francisco. Costs for fire control, including suppression action and damage, amount to an estimated $250 million annually. In a modern society with an ever increasing dependence on natural resources, it is obvious that such losses cannot be tolerated.

Yet in spite of what appear to be staggering losses, fire control agencies in the United States do an extremely effective job. They control about 95 percent of their fires at something less than 15 acres. These fires are the ones that you never read about in the newspapers or see on television. The ones that are widely reported are the small percent--five or less--that "get away" and that do about 98 percent of the damage. Normally these catastrophic fires occur

during periods of extreme weather, such as high winds, or follow drought and lightning storms where firefighting forces may be taxed beyond their limits. Such situations occur periodically in southern California and occurred last summer throughout the Pacific Northwest and northern Rocky Mountains.

Basically, the fire control agencies have three main jobs:

1. To maintain their present excellent record in controlling almost all fires.
2. To improve their effectiveness in controlling fires under extreme weather conditions.
3. To improve their ability under an improving weather regime to control the large fire that has occurred during a period of extreme weather.

Performing these jobs, however, is far from easy. A fire manager not only must decide how many men and tools will be needed in a given fire season, but he also has to make highly complex multiple and interdependent decisions, possibly involving thousands of men and many different kinds of equipment for a single or multiple fire situation. The growing complexity of the man-machine fire control system has created an increasing need for quantitative techniques and for the development of guidelines upon which fire control managers can base their long-range plans and tactical decisions. Also, they need to apply advanced systems analysis in project management techniques to strategical and tactical decision-making. Further, many of the problems they face are similar to those confronting a unit military commander. Each one is a decision-maker, whose decisions involve large numbers of men and large quantities of material. And often he is hampered by lack of information and practical economic criteria. Other major areas where the systems analysis approach may be used is in fire planning and determination of objectives.

At present, most fire control policy statements and objectives are subjective and couched in abstract terms. They vary from "Our policy is to control every fire as soon as possible" to "We don't even take suppression action unless we will log the area within 80 years." In the systems management approach, it may be possible to determine an infinite series of efficient solutions to fire control problems. However, unless we can adequately define realistic fire control objectives, we can never achieve an optimum solution. Many of these policies can't be defined precisely until there are more realistic methods for determining economic losses from fire. An important problem then is to develop better methods for evaluating the many incommensurable and intangible forest values.

If we can go back and analyze our successes during the past 30 or 40 years, we find that the percentage of medium-sized fires--from 15 or 20 acres up to perhaps 10,000 acres in size--has dropped considerably. The percentage of small fires--something under 15 acres--has increased rather dramatically. And the percent of very large fires has undergone very little significant change. In other words, we have made small fires out of the medium-sized fires, but haven't made too much headway with the very large fire usually burning under extreme conditions. One of the chief reasons for success has been the use of the trained, organized fire suppression crew and the increased mobility of firefighting forces. The organized crew hasn't always been easy to justify because of the sporadic and seasonal nature of fire control problems. However, it forms the nucleus around which most of our firefighting is done. It also provides a trained cadre for expansion to a large fire organization. When fires are small, the suppression organization is relatively simple (CHART 1). One man--the fire boss--will control one or more fire suppression crews and may have other equipment, such as bulldozers and tank trucks. He makes his own fairly simple tactical and strategic decisions, and forms his own information processing service. And when extra supplies and equipment are needed, he can call upon the agency dispatcher to send

them. One of the keys to success for such initial attack forces, as they are called, is efficient and fast dispatching. Therefore, it is reasonable to assume that anything we can do to increase dispatching efficiency will make a unit more efficient. Consequently, we are developing an automated initial attack model, using automatic data processing equipment.

Present allocation of forces is based on the dispatcher's knowledge of his district's topography, variety and distribution of fuels, weather, past history of local fires, and availability of suppression crews. He may also use maps, hour control zones, fuel types, and land values, as well as recent guides for manpower allocation. The present dispatch model is based on network analysis or graph theoretic concepts. The forest road system is modeled as a directed plainer graph (CHART 2). Arcs in the system are directed because of the effect of road grade on travel times with heavy firefighting equipment. An algorithm presented by Pollack and Wiesbenson in the OPERATIONS RESEARCH JOURNAL (March-April 1960) is used to calculate a minimum spanning tree rooted at the origin of the fire (CHART 3). Nodes in the network serve as a basis for inventory of firefighting resources. The model permits rapid update of the inventory by moving resources from node to node. Equipment dispatched to the fire is shown located at the node nearest the fire and usually not available for subsequent dispatches to other fires. For efficient operation, the computing equipment must be real time with exceedingly fast responses.

But there are some real constraints on a practical system.

1. Any system to be practical must be based on real time. The dispatcher must be able to decide immediately, based on the fire situation as it exists at the moment.

2. The system must be easy to operate. It must operate in conversational language and be easily used by the dis-

ORGANIZATION FOR MEDIUM CREW FIRE

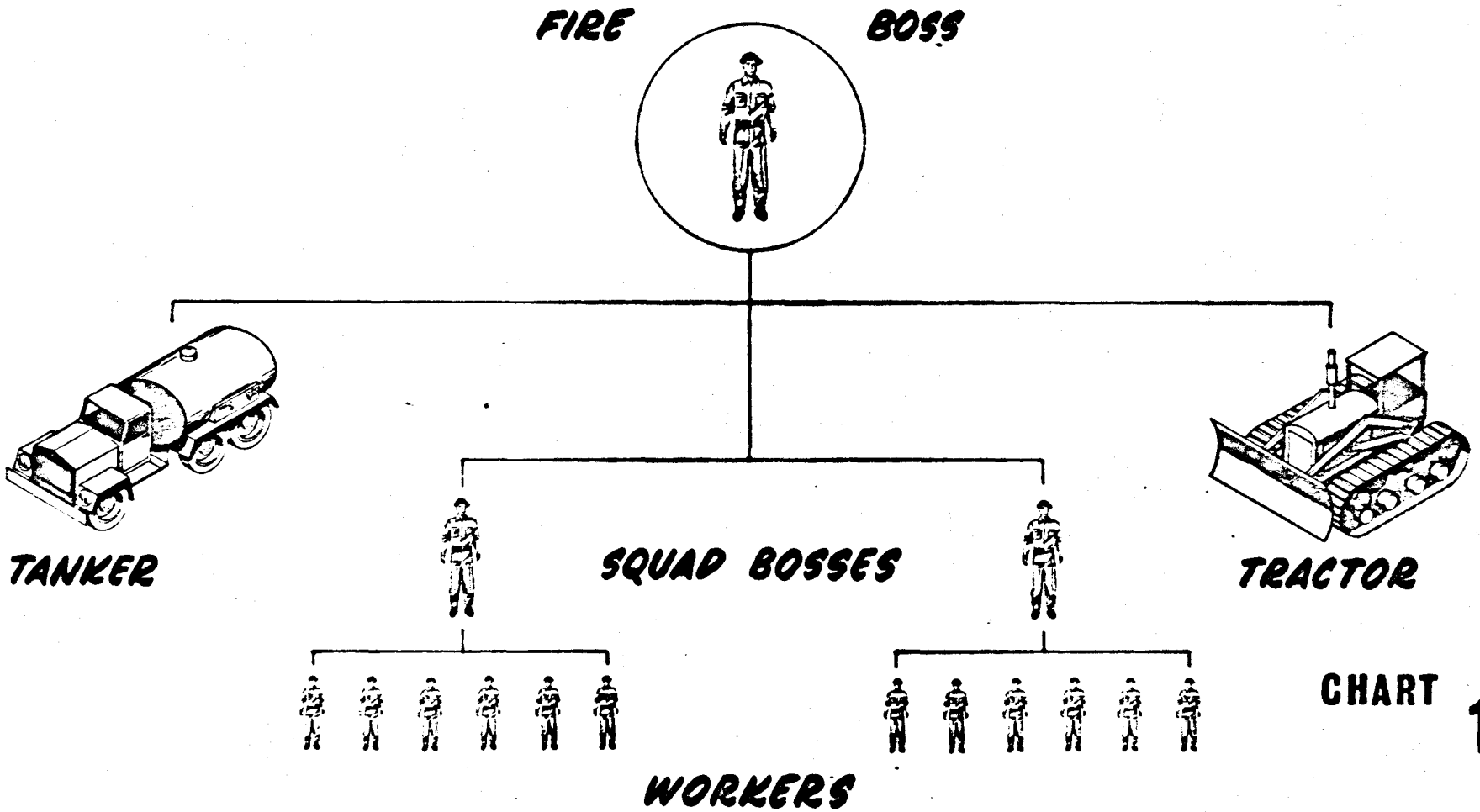


CHART 1

BASIC NETWORK OR GRAPH

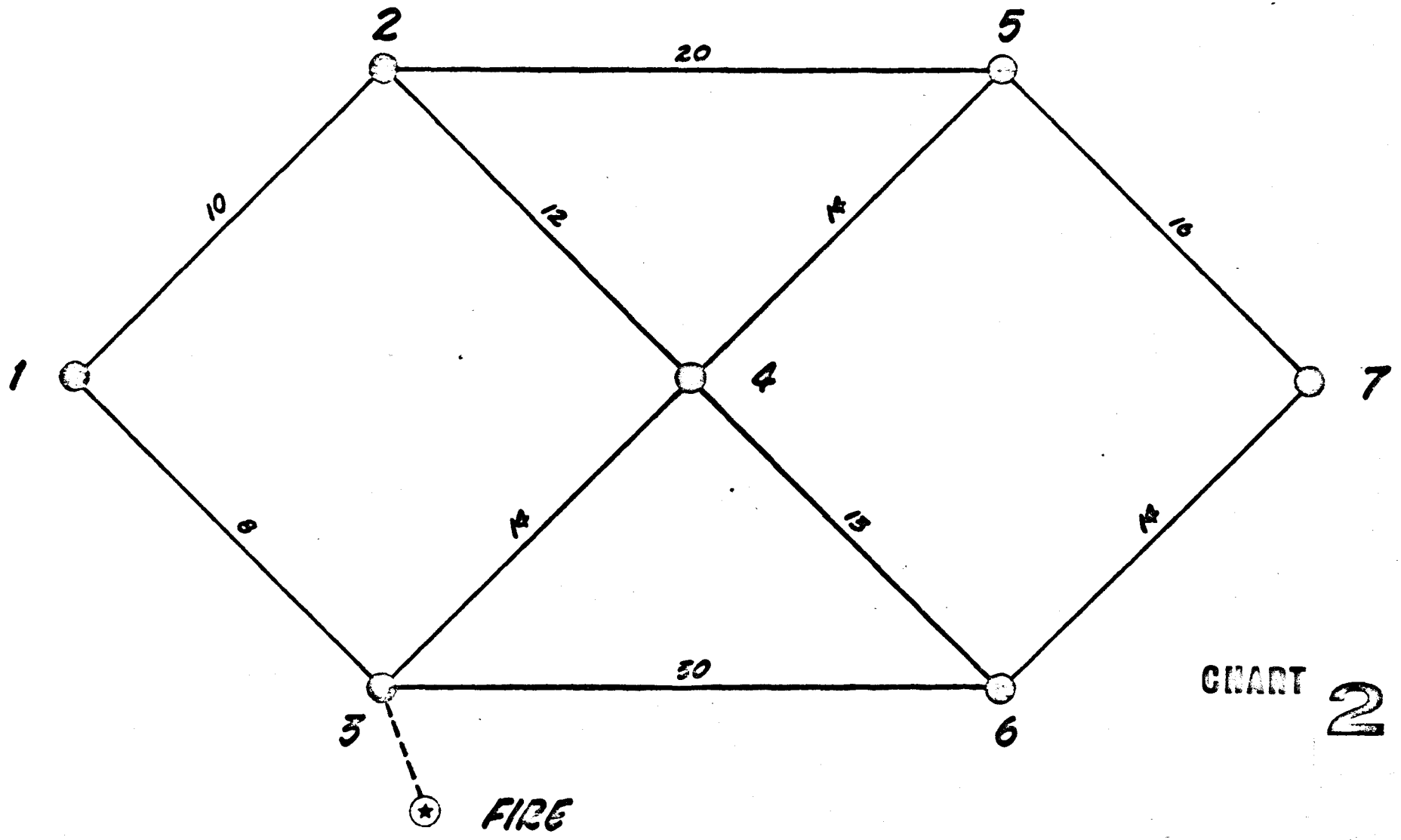


CHART 2

TYPICAL SPANNING TREE (MIN.)

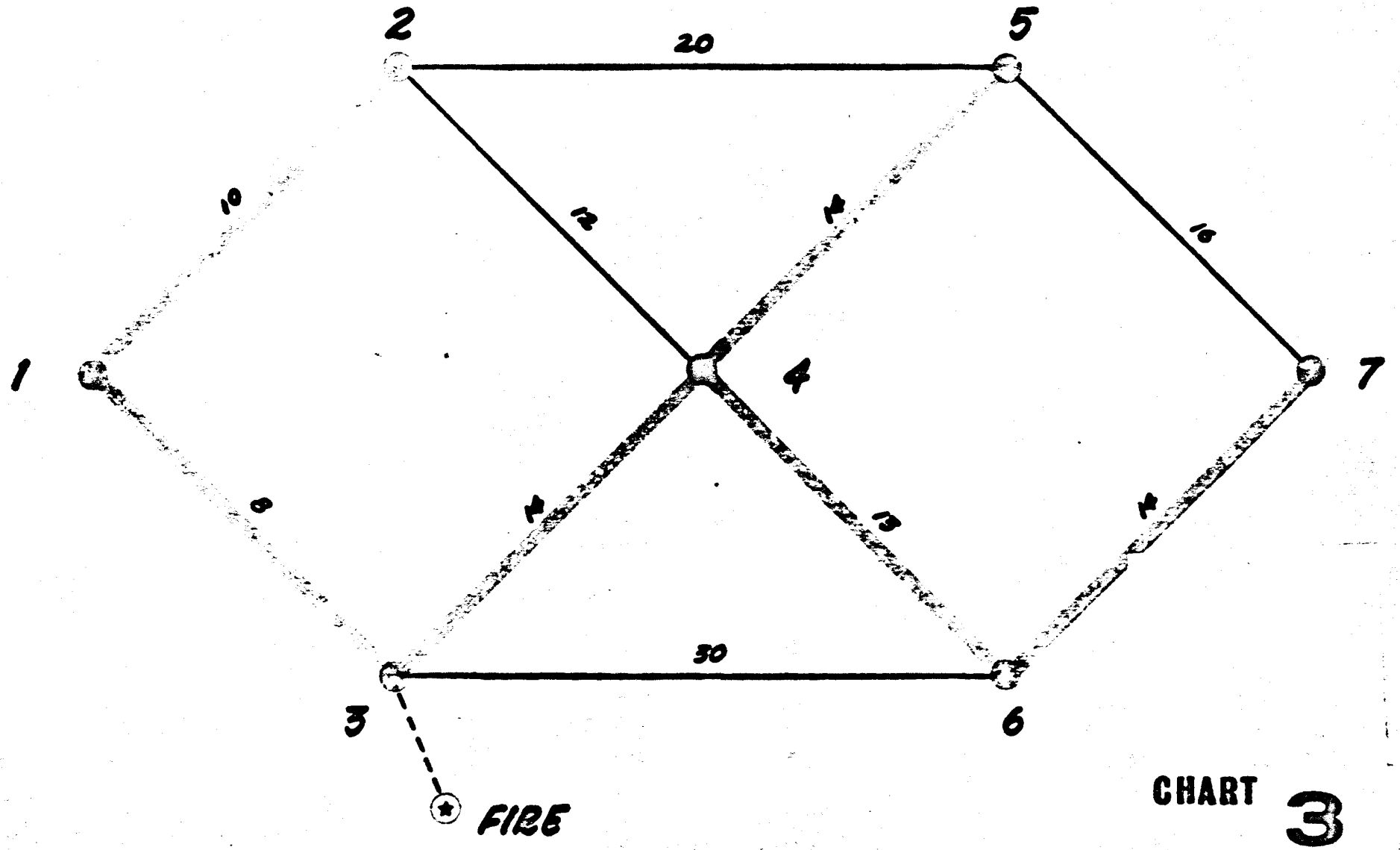


CHART 3

patchers that are on the job today.

3. The systems must be fail-safe. One of the first questions that we have been asked is: "What happens if the computer breaks down or the power goes off?" The dispatcher will need a typewritten computer-generated record of all that happened so that vital information won't be lost. Such a record should be at least as good as the log the dispatcher now ordinarily makes.

4. The system must be easy to update. It must be easy to put in changes in crew location dispatches and eventual changes in weather and fire behavior.

5. The system should be useful as a fire planning tool. It should be adaptable to planning crew locations, road system modifications, and the dozens of other potential changes that can occur in the fire control area.

6. The system should be useful as a training tool. The computer system should be capable of simulating fire conditions so that it can be used as a training aid for new personnel.

Initial models of the program were developed on an IBM 7040 computer. A second, real time working system is adapted to Tymshare, Inc., using a teletype terminal and SDS 940 computer. A third version is being programmed for the CDC 6400 computer. Hopefully, one or two of the systems will be in operation this summer.

Now let us look at what happens if the fire is not controlled at initial attack and becomes very large (CHART 4). This chart shows a rather complex organization for a major campaign fire. You will note that there are basically four organizations:

1. Line, or operational, forces.

2. Service and supply.

3. Plans and records.

4. Fiscal.

Such a system permits considerable flexibility, but demands a great deal of decision-making skill. First, let us describe how we can bring such a force into existence, considering that it may involve hundreds or perhaps thousands of men and many diverse pieces of equipment. We should also bear in mind that in a critical situation, such as occurred in the Pacific Northwest last summer, there may be many such organizations being developed almost simultaneously. A dispatcher, coordinating the movement of resources over a large geographical area, is confronted with the problem of multiple sources of supply and multiple demand--a typical transportation problem (CHART 5). A typical situation associated with the fires in the Pacific Northwest was the transport of Indian firefighters from various parts of the country. They came from as far away as Alaska and Florida. As far as we know, it is the first time that Eskimos, Navajos, and Seminoles worked together side by side. This cooperation caused someone to comment, "If Sitting Bull had been able to amass the tribes the way the Forest Service had done, the winning of the West would have been set back 50 years!"

Here again we are using network analysis in the form of a Hitchcock transportation problem (CHART 6). The Hitchcock problem uses the linear programming dual to determine the least cost solution to a maximum flow problem. In the problem arcs with fixed upper bounds but zero cost, determine the capability of a source to supply resource. Likewise, upperbounded zero cost arcs designate the capacity of a unit, in our case a fire, to receive resources. Source and sink nodes are linked by arcs with infinite capacity but sometimes with a lower bound and with a cost representing transportation distance. This arrangement permits a flow when price constraints have been met. Primed sink nodes represent the resources kept on standby to protect the source's fire protection area. Lower bounds on an arc from m to n assures that

ORGANIZATION - LARGE FIRE

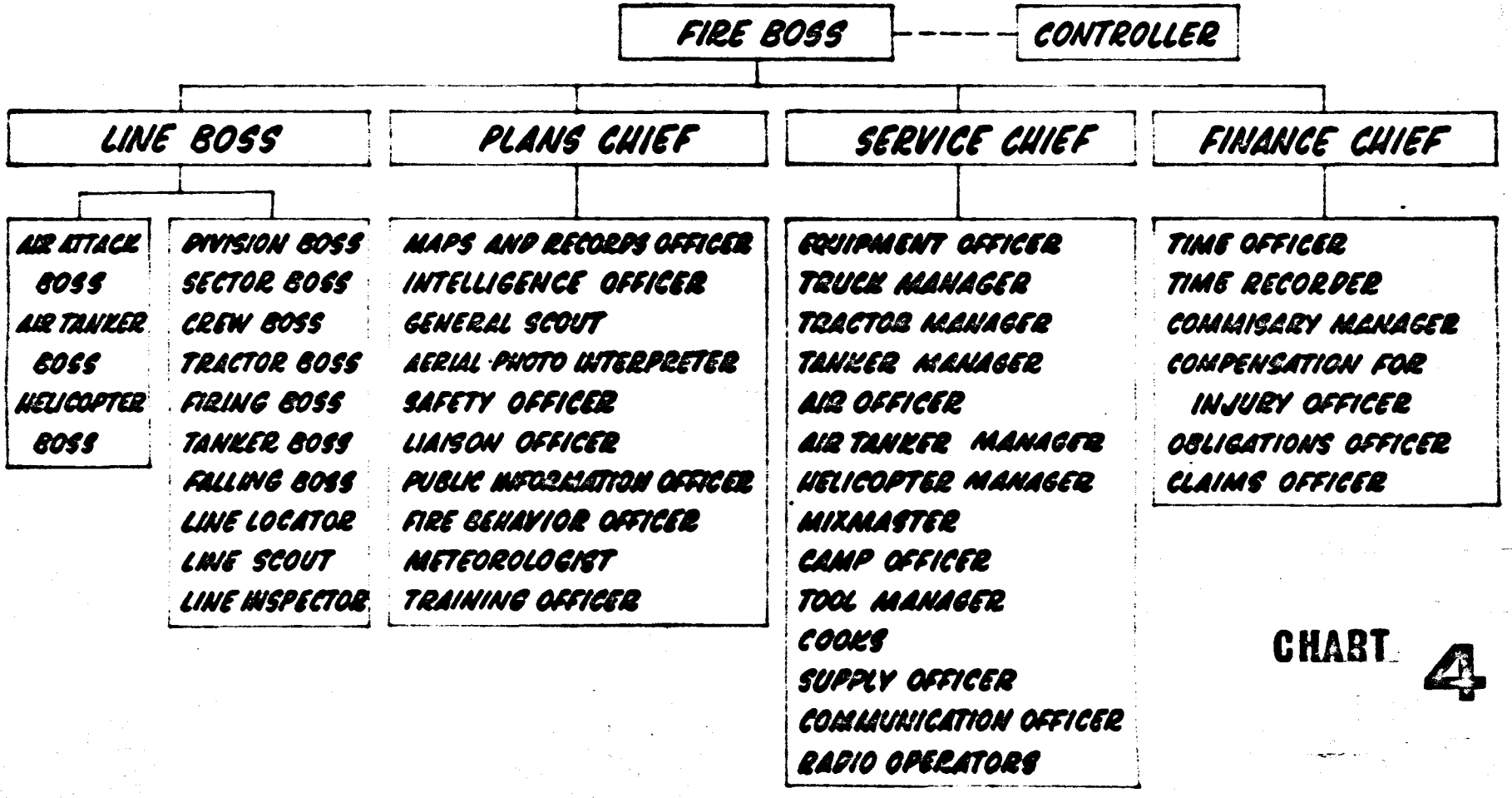
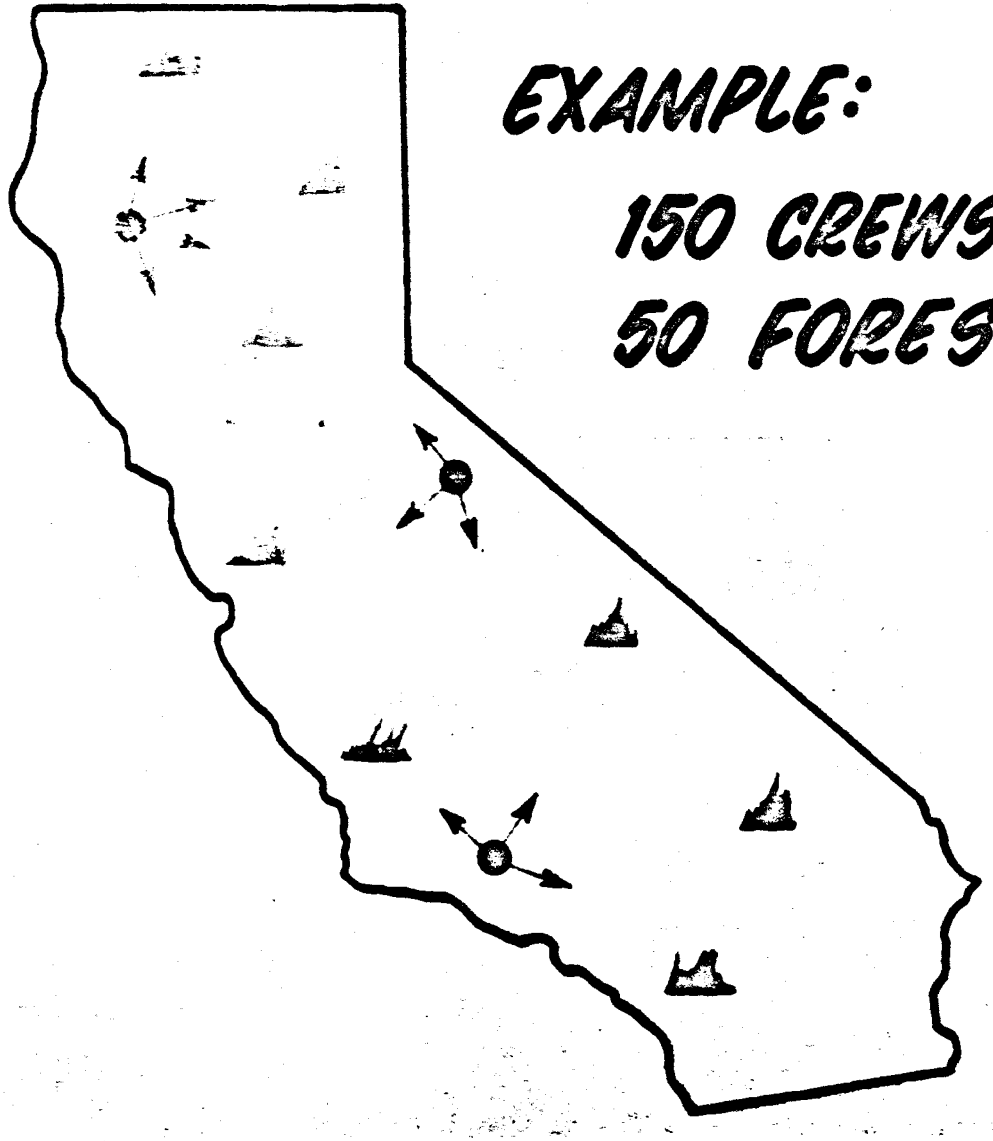


CHART 4

MULTIPLE MANPOWER SOURCES
MULTIPLE FIRE



EXAMPLE:

150 CREWS IN 30 CAMPS
50 FORESTS

CHART 5

COST AND PENALTY DATA FOR HITCHCOCK PROBLEM

C_{ij}

i \ j	A'	B'	C'	D	E	
A	0	5	3	8	2	5
B	5	0	4	3	4	4
C	3	6	0	2	6	6
	1	5	2	6	1	

SUPPLY POINTS

DEMAND POINTS

TEAMS AVAILABLE

TEAMS NEEDED

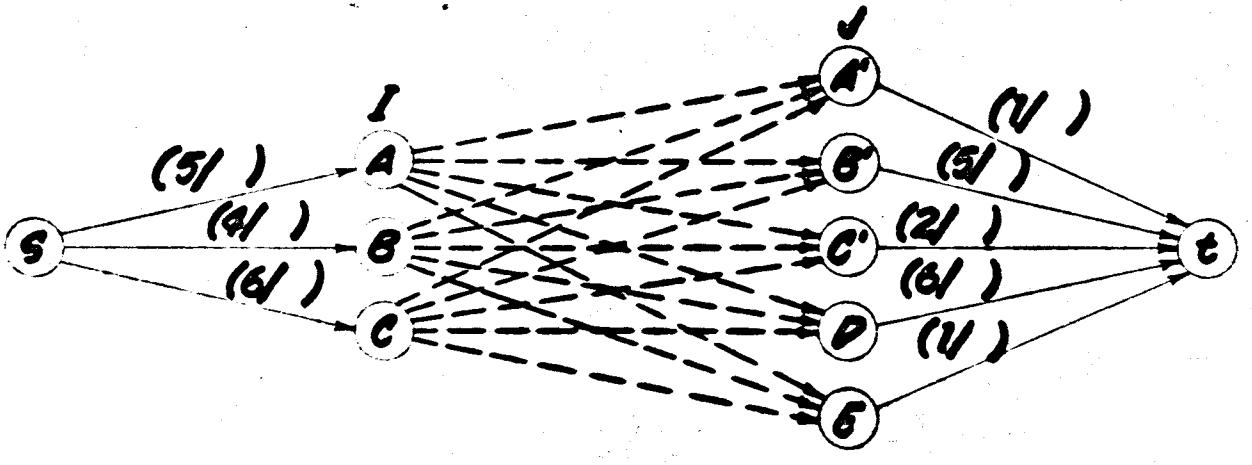


CHART 6

a given number of resources, such as personnel, will always be kept at home. This brings up an interesting consideration of values other than transportation costs. Optimum solutions have been found that send all resources from a source to another location and replace them with other resources. When the resources are skilled men who may know the local terrain and firefighting conditions intimately, this may not be desirable. Consequently, the lower bound produces what may be a less-than-optimum allocation in resources from a cost standpoint but assures the retention of local needed skills. There are several reasons for using network analysis rather than a linear programming approach to the transportation problem. They include the following:

1. Computation requirements for maximum flow problems require perhaps one-third the amount of machine time than is required by equivalent linear programming problems.

2. As long as source and sink capacities are expressed in integers, optimum solutions will be in integer values. Thus we won't be dispatching fractional bulldozers.

3. The system of arcs producing a path from source to sink is perhaps more intuitive to many fire control people than is a linear programming tableau.

4. The network approach relates more closely to the Forest Service's present road system planning concepts based on network analysis. For example, Forest Service timber sales now being studied on the basis of a trans-shipment problem where logs come from the woods to one of several possible sawmills and from there to shipment points or lumber markets.

Assuming that we now have an operating fire control organization on a large fire, we obviously need to use it in an efficient and effective manner.

Large fires (campaign fires) are fires for which first attack efforts have failed and which, we will assume, are partly or completely uncontrolled. The problem is to implement a fire suppression effort designed to stop the fire spread quickly and efficiently and bring the fire under control.

Control System Model

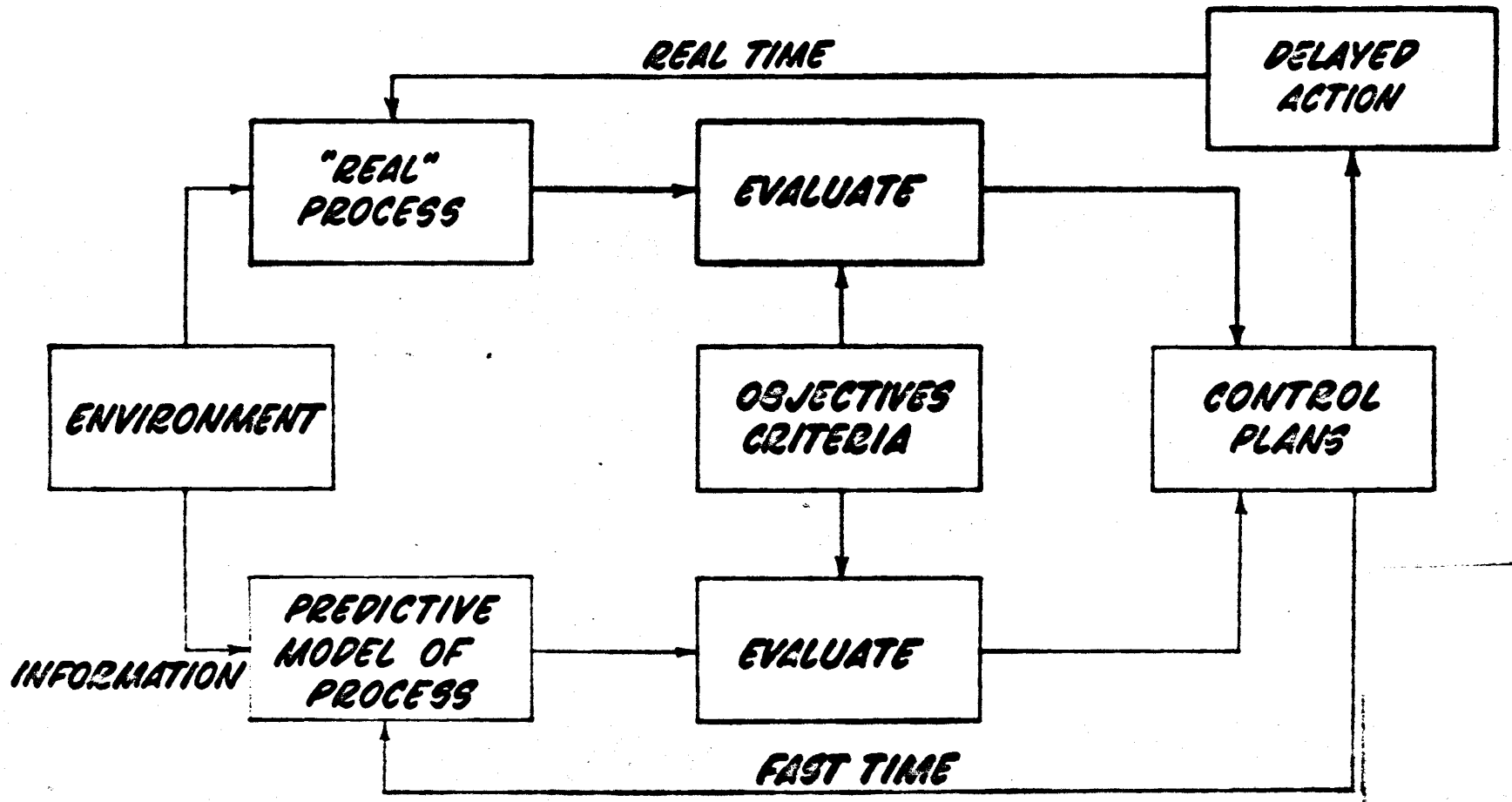
It is instructive and useful to examine the large fire suppression problem as a control system problem. CHART 7 shows a generalized control system model in block diagram form which applies quite well to the fire suppression system problem. The connection of the generalized model to this problem will be shown below.

To enter the system model, tentative control plans are introduced. A predictive model of the process to be controlled is included, along with information about the environment. The output generated is an estimate of the output of the real process under the same circumstances. An evaluation process using the objectives and criteria for the system may result in modification of the control plans. The loop is iterated until a satisfactory evaluation results. The control plans can then be implemented by the real process. The delay in implementation is shown explicitly by the "delayed action" block. The "real" process is affected, of course, by the "real" environment, and an output occurs. This output is evaluated by a procedure which is the same as, or analogous to, that used for the model output.

The output of the process may not be evaluated as satisfactory. The reasons are many; for example, the predictive model is certainly not a complete or faithful model of the real world. Another likely source of error is the information about the environment, which is used to drive the model process. In any case, a less-than-satisfactory evaluation of the process outcome is fed back into the planning activity where modifications are made.

CHART 7

CONTROL SYSTEM MODEL



The complete system operation is iterated until all objectives and criteria are satisfied and a state of completion is reached.

Fire Suppression Problem

An example of a tractable fire suppression problem is shown in CHART 8. Before proceeding, a few definitions may be needed. The fire suppression process comprises a variety of activities aimed at completing a control line around the fire perimeter. Such a control line consists of natural and man-made fire barriers. Commonly, such barriers are cleared pathways or trails produced by crews of men with hand tools or by tractors.

In the situation pictured here, the control problem begins at 0 hours. Control line has been completed around the lower portion of the fire perimeter. The problem is, first, to predict the spread of the fire over the next working period. Next, a proposed final control line is located. The line construction job can be broken down in various ways. Wherever possible, the line is "tied in" to preexisting natural or man-made fire barriers, as is shown here at the top of the figure. The effect in this case is to partition the problem into two independent fire suppression problem areas. In each area two tasks have been shown. Task 1 of Area 1, for instance, might be in a steep, rocky region where hand crews must be used. Task 2 might be located along a more easily traversed route where bulldozers could be used to clear the fireline.

The physical problem description is completed by designating several resource pools. These are known quantities of men or machines which are available for work on this job. From each such pool, travel times to various parts of the control line are known.

Finally, we note that value judgments can be made concerning the importance of controlling the fire in various areas. To illus-

trate this, a town is shown being threatened by the fire in Area 2. To proceed with a methodical analysis of a problem of this kind, it is necessary to attach relative utility values to controlling of the fire in the independent fire areas.

Predictive Model

CHART 9 shows in more detail the modeling process which was included in the first chart. We can now connect the modeling process to the fire control problem.

A set of task descriptions which we call here the "strategic plan" is generated. By using this information along with fire spread predictions and relative utilities, we can allocate the available resources optimally to the various tasks. The allocation process yields two major outputs: (a) resource allocations (a "tactical plan") result, along with probability estimates for completion of the various tasks within the time constraints; and (b) the expected utilities for the control areas and for the complete problem also are generated.

Evaluation of the plans is now possible on the basis of objective probability estimates and expected utilities. An "unsatisfactory" evaluation can be remedied by revision of the strategic plan, mobilization of additional resources, or both.

Allocation Problem

A mathematical statement of the allocation problem to be solved can now be given. The criterion for optimality is maximization of the expected utility of control for the complete control problem.

The utility function to be maximized, the resource constraint equations, and definitions of variables are shown in CHART 10. The

EXAMPLE OF SUPPRESSION PROBLEM

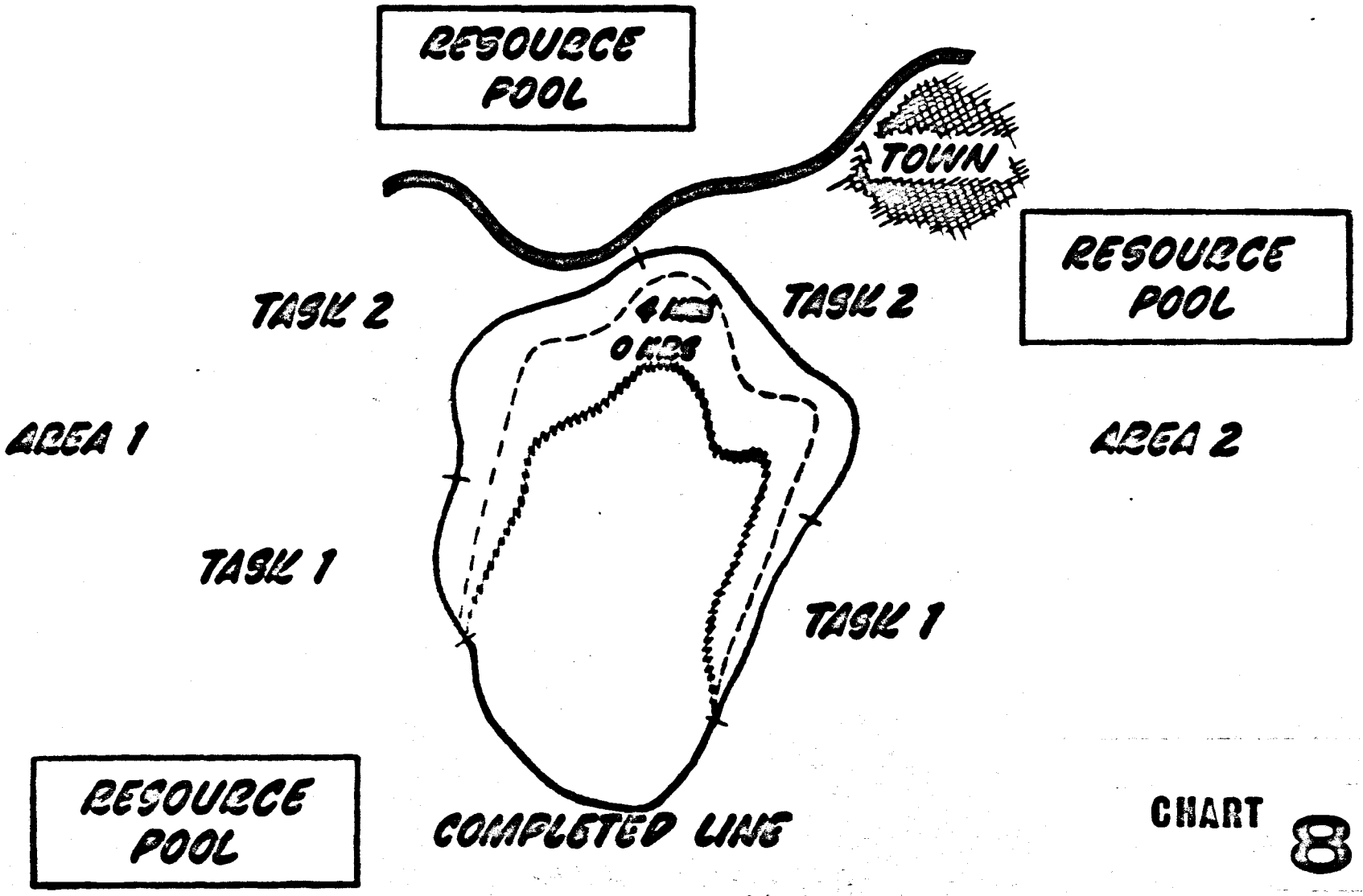


CHART 8

PREDICTIVE MODEL

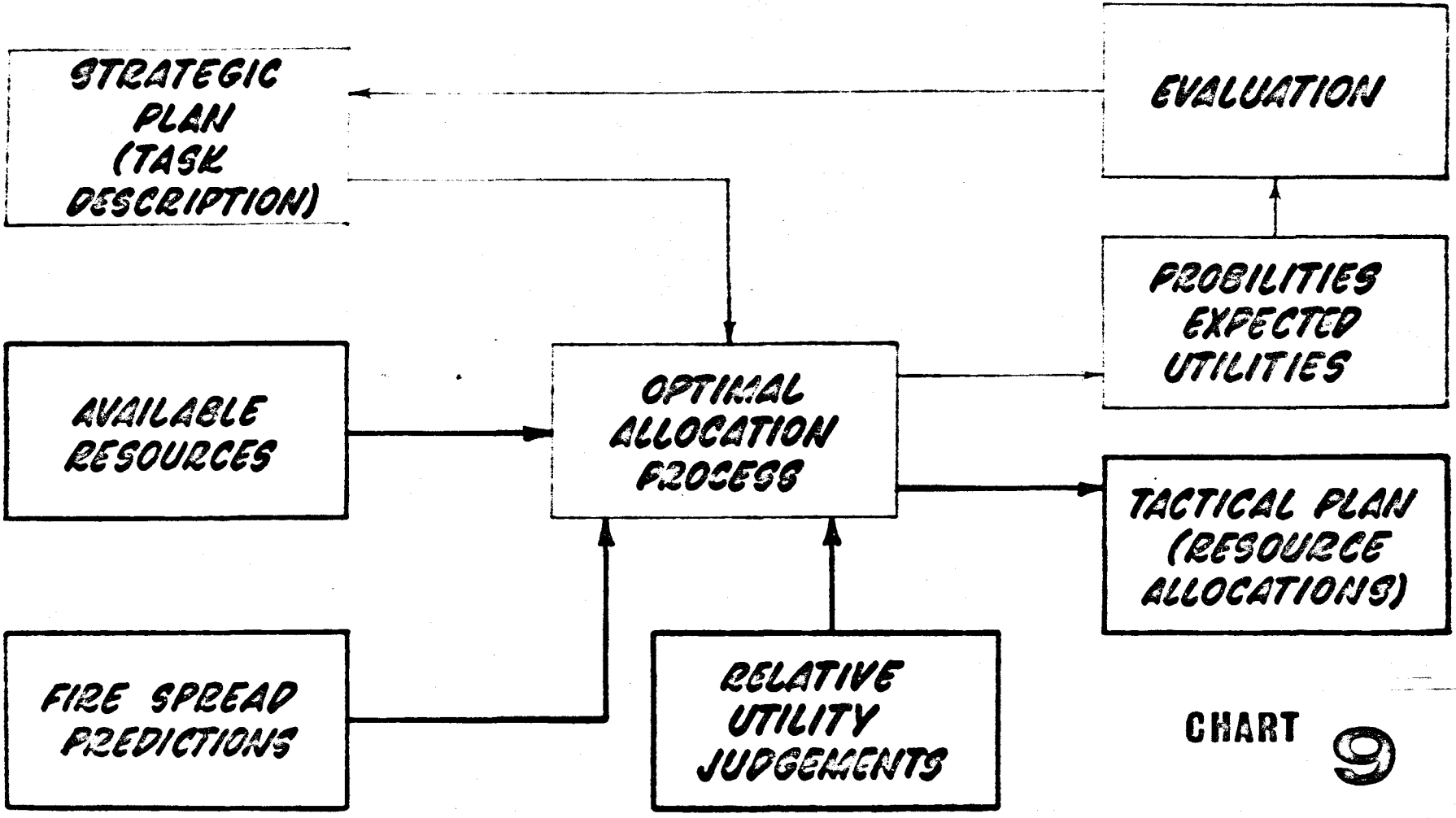


CHART 9

UTILITY FUNCTION

$$U = \sum_{j=1}^{M} V_j \prod_{k=1}^{N_j} P_{jk} \left(\sum_{i=1}^{L} E_{ijk}\, Y_{ijk} \right)$$

$$\sum_{j=1}^{M} \sum_{k=1}^{N_j} Y_{ijk} = Q_i \,, \quad i = 1, 2, \ldots, L$$

i IS RESOURCE POOL INDEX

j IS AREA INDEX

k IS TASK INDEX

CHART 10

V_j IS UTILITY FOR CONTROL OF FIRE IN AREA j

P_{jk} IS PROBABILITY OF COMPLETING TASK$_k$ IN AREA$_j$

Y_{ijk} IS QUANTITY OF RESOURCE FROM POOL i ALLOCATED TO TASK $_k$ IN AREA j

E_{ijk} IS EFFICIENCY FACTOR FOR Y_{ijk}

Q_i IS QUANTITY OF RESOURCE IN POOL i

probability functions involved here are derived from field data on the performances of men and machines. Implicit in these functions are the effects of elapsed work time, the kinds of equipment being used, and the effects of the environment on production rates.

This problem has been programmed for computer solution using the Lagrange Multiplier method. Plans for the near future call for modification of this program to include a wider range of tasks and to adapt the program for field use.

Fire INFORMAP Data System

The INFORMAP System is being developed for storage, retrieval, and display of a variety of data for National Forest lands. The experimental INFORMAP System now under development is capable of handling information of the kinds shown in CHART 11. Most of the data of interest are presently available on special maps. Such data are used for a number of forest management purposes, in addition to forest fire management.

As we move into the era of computer-based information and management systems, it becomes increasingly necessary and valuable to have this kind of information in a compatible form. Provided the necessary equipment is available at the required locations, the advantages of computer-based display systems over conventional maps, for many purposes, are clear. Among these advantages are the ease of selecting a particular collection of information for display and the speed with which the information can be obtained and displayed.

The availability of environmental data in digital form is crucial to field use of computer-based fire suppression aids, such as the allocation model discussed previously. Another, even more critical, need is for inputs to computations of fire spread, as we shall see.

Fire Suppression Information Systems

In addition to INFORMAP, a number of information systems of value in fire suppression are shown in CHART 12. These systems are either presently operational or are under investigation or development.

Infrared mapping of fires from aircraft is operational on an experimental basis. Project FIRESCAN at the Missoula (Montana) Forest Fire Laboratory has developed such a system. Current information on the perimeter locations of going fires is extremely valuable for fire management purposes. Such information will be essential for initializing and updating the computer-based fire spread simulator discussed below.

Aerial observation of fire progress and fire control progress is a standard procedure. Again, such information can comprise valuable updating inputs to computations.

Automatic weather stations placed in proximity to fires soon will be valuable adjuncts to area weather observations. Fire behavior is very strongly influenced by local weather factors, and this kind of information is required for prediction of fire spread patterns.

Lastly, we have listed inventory systems. If automatic data processing equipment is available at fire locations, application to inventory, timekeeping, and similar business management jobs undoubtedly will be made. The requirements for accurate and current resource status in the allocation model applications previously discussed probably will require some record-keeping in computer storage, for automatic updating and access.

INFORMA' SYSTEM

EXPERIMENTAL DATA STORAGE AND RETRIEVAL ON NATIONAL FORESTS

AVERAGE INTENSIVE PARAMETERS IN 10 ACRE CELLS

- ALTITUDE
- SLOPE
- ASPECT
- FUEL (VEGETATION) TYPE

  ETC.

EXTENSIVE INFORMATION WITHIN 2/3 ACRE

- FIRE CONTROL FEATURES
- HIGHWAYS, ROADS, TRAILS
- RIDGES
- STREAMS
- ETC.

CHART 11

INFORMATION SYSTEMS

INFORMAP DATA SYSTEM

IR MAPPING

AERIAL OBSERVATION

AUTOMATIC WEATHER STATIONS

INVENTORY SYSTEMS

supply data to INF. - can display like any other data

CHART 12

Fire Spread Simulation

At numerous points in the preceding discussion, the value of predicting fire spread has been mentioned. At the present time, fire spread on wildland fires is estimated by rules-of-thumb and by the judgments of fire behavior experts. A reasonably accurate fire spread computation capability would be of great value. Since we are beginning to talk about having computer facilities in the field, it becomes possible to propose such capabilities. Another factor that contributes to the feasibility of this goal is the development of the INFORMAP data base for areas of interest.

As shown in CHART 13, there are three classes of fire spread models which have been proposed or used. Geometrical models, the first class, are the simplest possible approach. The fire perimeter is described by a simple geometrical figure, and the fire spread is represented typically by expansion of the figure. Examples would be expanding circles or ellipses.

The second class of fire spread models are physical models. Fire spread is, of course, an extremely complex physical phenomenon. Much effort has been and is being expended to understand the physics of wildland fire behavior and to develop mathematical representations. It is not surprising that no generally applicable models have resulted. The physical fire spread models which have been proposed have been used, typically, to explain the results of laboratory experiments carried out under carefully controlled conditions.

A third class of fire spread models uses a contagion mechanism. The area under consideration is subdivided into small cells. Each cell may be in one of several combustion states. Fire spreads from a "burning" cell to an adjacent cell at an instant in time which depends upon the relative states of the two cells and upon some

function of position and time. The spread may be made stochastic by the imposition of probability distributions on appropriate spread parameters.

A computer program for a contagion algorithm has been developed at the Riverside Forest Fire Laboratory and is being evaluated at the present time. Three cell states are designated by a time-to-go variable, t_{ij}, for cell (i,j), as shown. For each cell, elapsed times for spread across the cell must be specified in the directions of adjacent cells. These times depend upon environmental parameters and fire behavior principles.

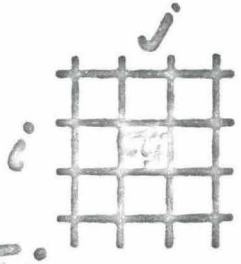
We expect to develop a complete experimental model of this type for evaluation within the next year.

FIRE SPREAD SIMULATION

CHART 13

THREE APPROACHES
- GEOMETRICAL
- PHYSICAL
- CONTAGION

CONTAGION MECHANISM



"STATES" OF CELL (i,j) ARE:
- POTENTIALLY ACTIVE $\tau_{ij} > 0$
- ACTIVE $\tau_{ij} < 0$
- PASSIVE $\tau_{ij} = 0$

ELAPSED TIMES FOR SPREAD ACROSS CELLS COMPUTED FOR VARIOUS DIRECTIONS
- GEOGRAPHICAL PARAMETERS FROM INFORMAP
- FIRE METEOROLOGY FROM WEATHER AND FIRE BEHAVIOR PRINCIPLES